Searching for new short range forces using optically levitated microspheres

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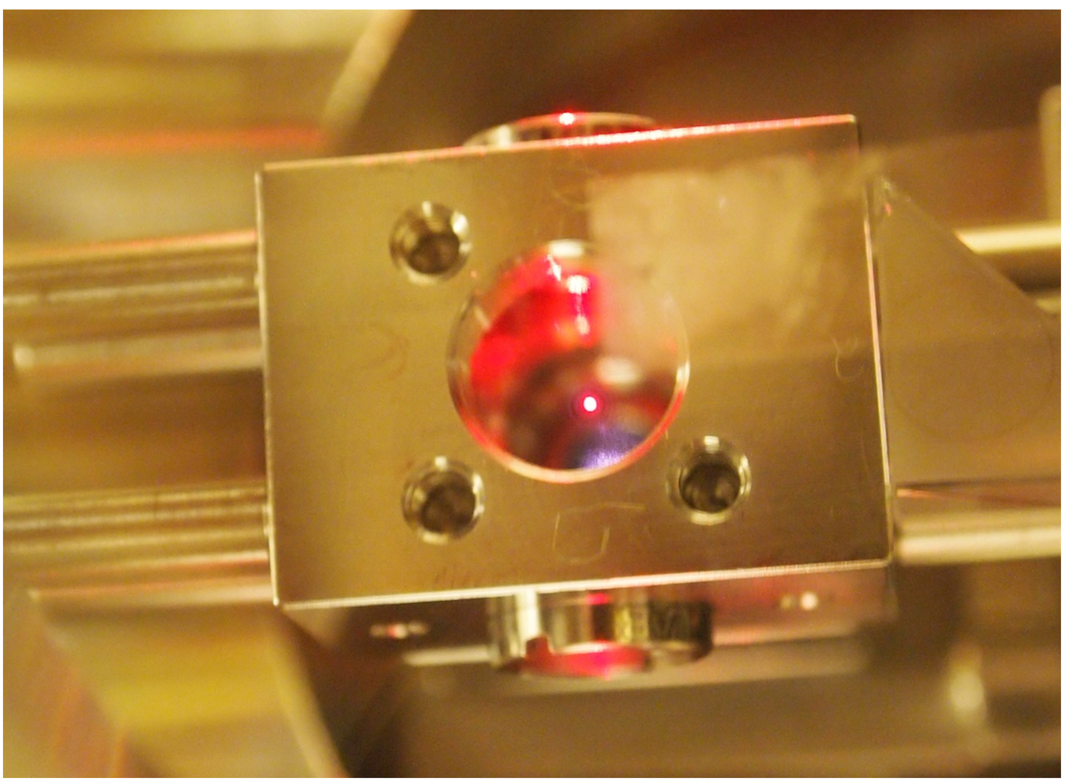
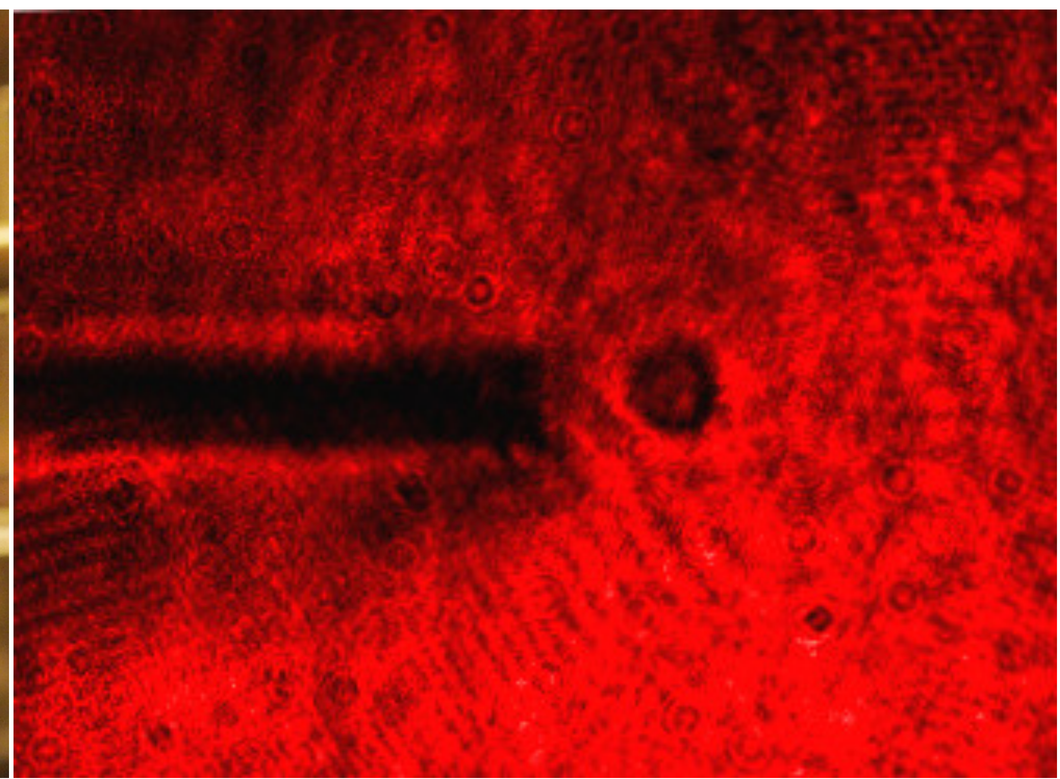
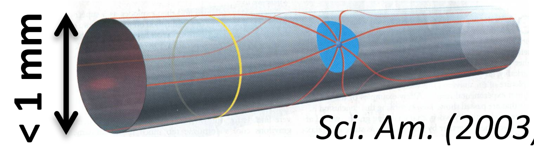
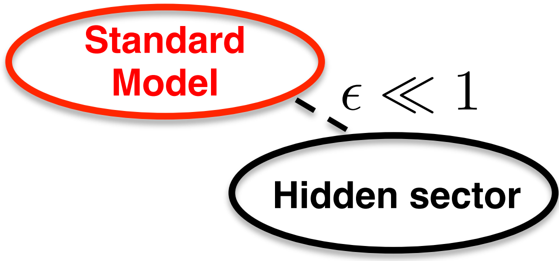


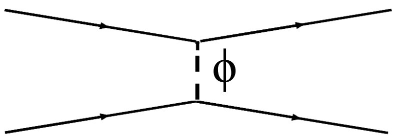


Short-range forces

- Although the WIMP hypothesis remains well motivated, it is possible that it will not ultimately be confirmed
- Searching for new short-range forces can probe a variety of models of dark matter and dark energy that can be difficult to test in other ways:
    - Large extra dimensions (KK dark matter)
    - Hidden sector dark matter
        - New forces mediated by dark photons or light millicharged particles from the dark sector
        - Heavy, stable millicharged particles bound in matter
    - Exchange forces from new scalars (e.g. scalar axions, dilatons, radions, axions, ALPs, …)
    - Dark energy models with screened scalars (e.g., chameleons, symmetrons, galileons, …)







Given the large number of mechanisms for generating such forces, this is an interesting (and largely unexplored) parameter space for new physics!

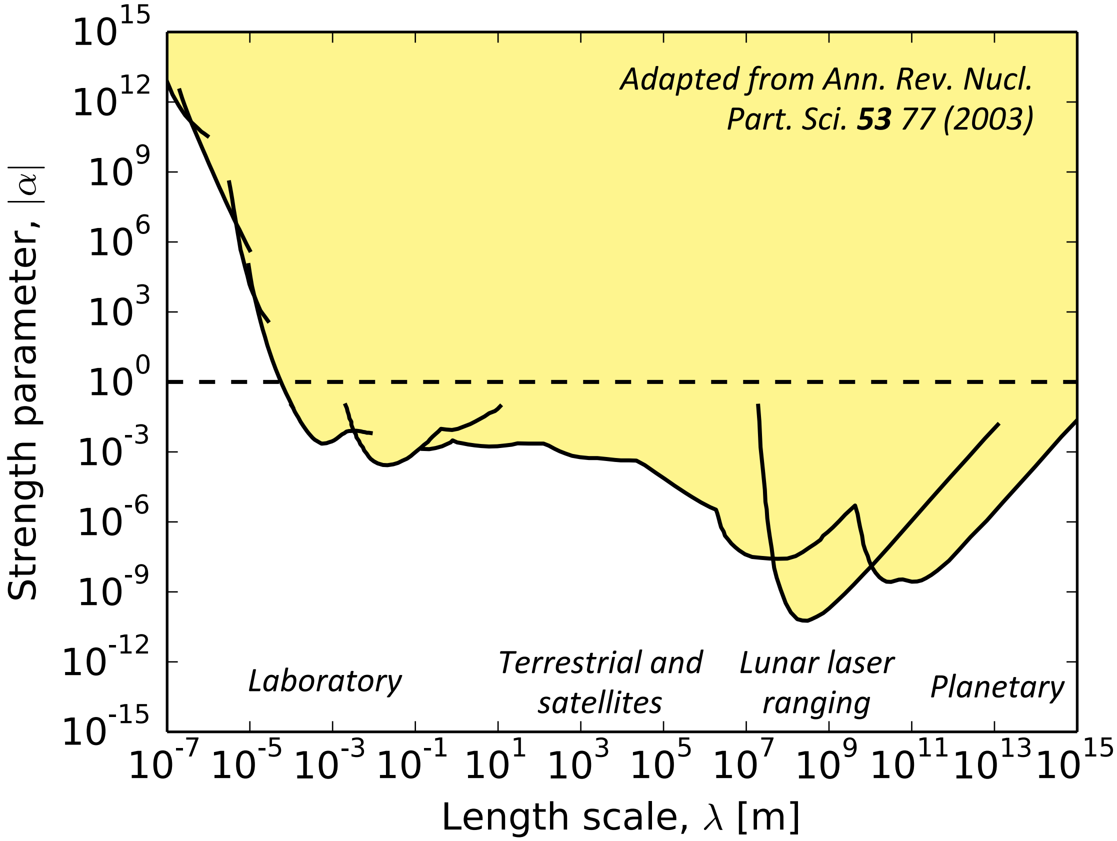
Experimental constraints

- Typically parameterize non-Newtonian potential with Yukawa form:

$$V(r) = -\frac{Gm_1m_2}{r}\left(1 + \alpha e^{-r/\lambda}\right)$$

- Strong limits from terrestrial and astrophysical tests exist at large distance

Current experimental constraints on non-Newtonian forces:



- For short length scales, constraints are much weaker: $\alpha \lesssim 10^{10}$ for $\lambda = 1\ \mu\mathrm{m}$
- May be possible to significantly improve sensitivity at micron length scales in next few years
- This will allow us to probe substantial regions of previously unexplored parameter space

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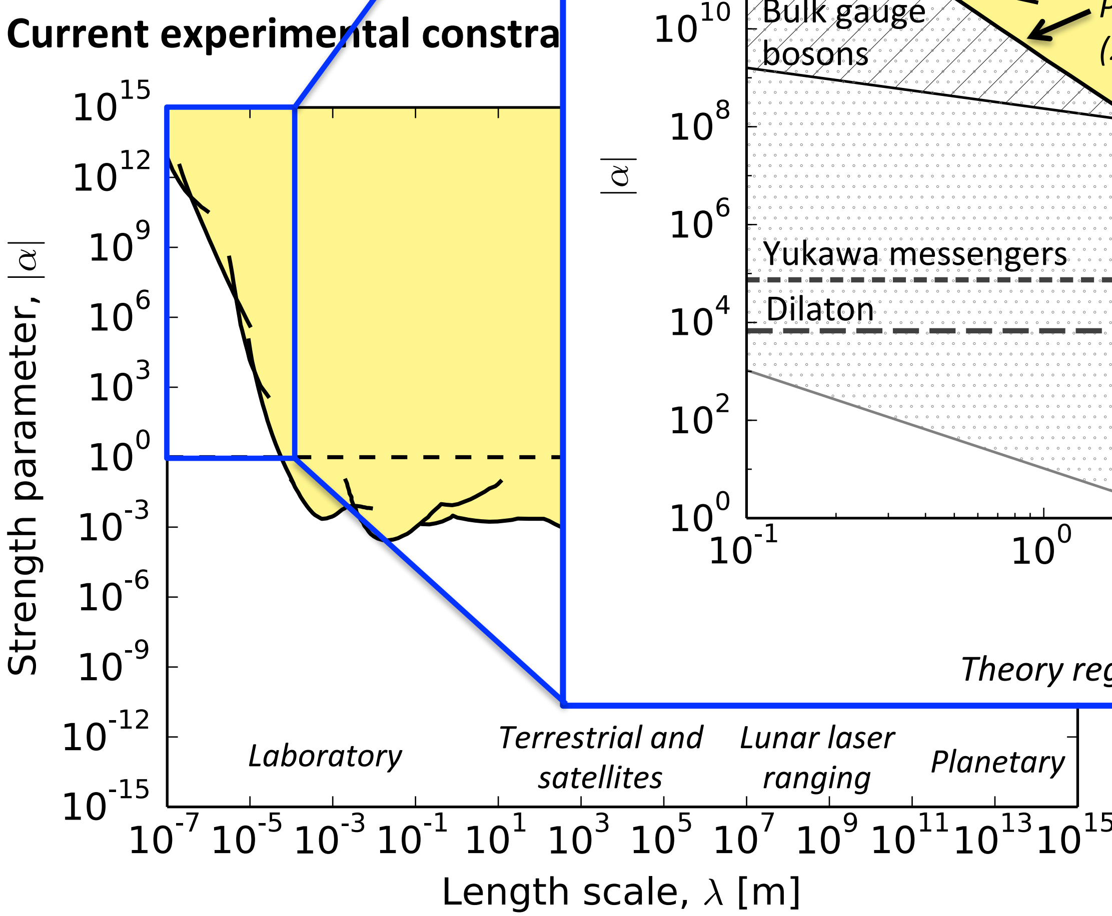

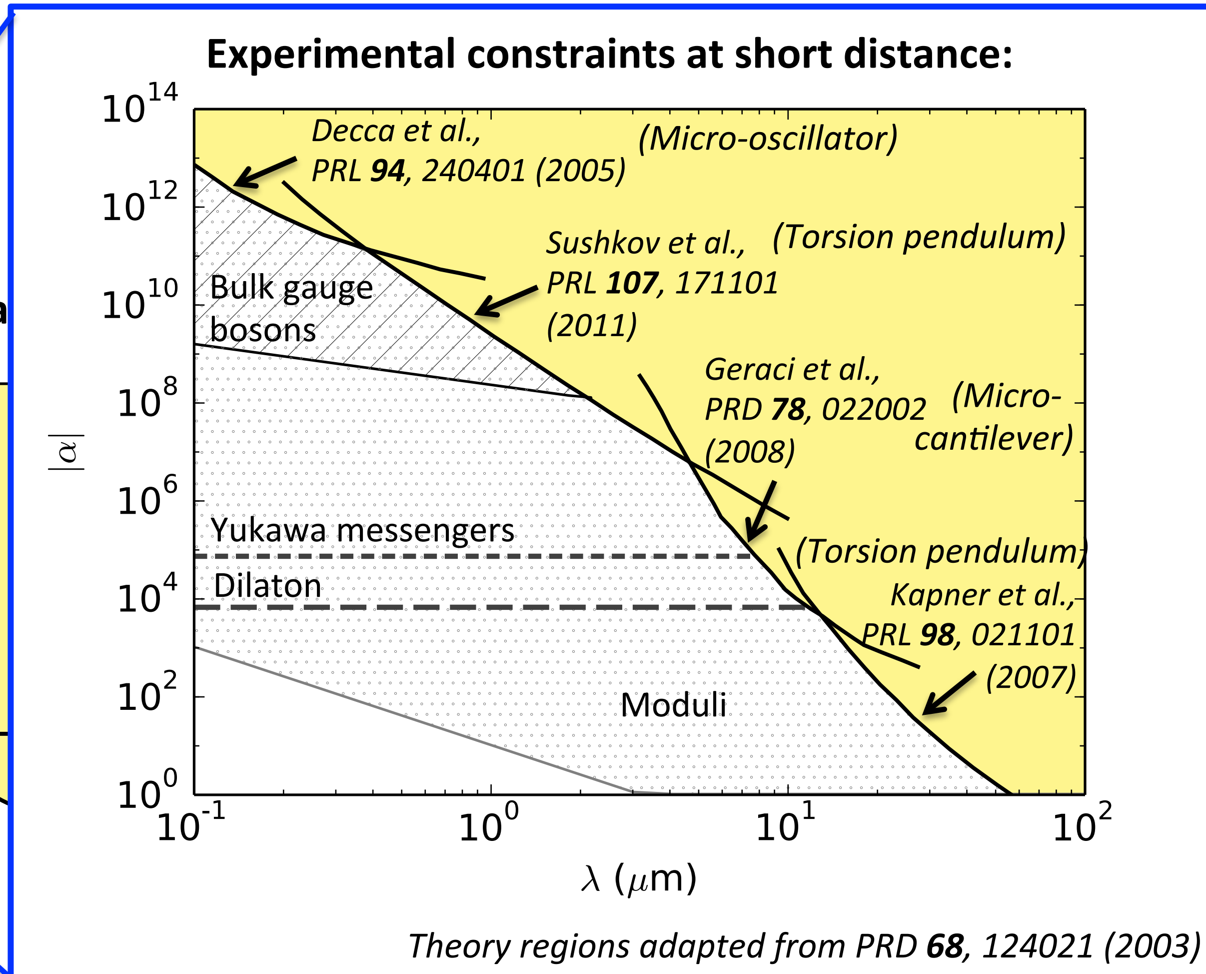

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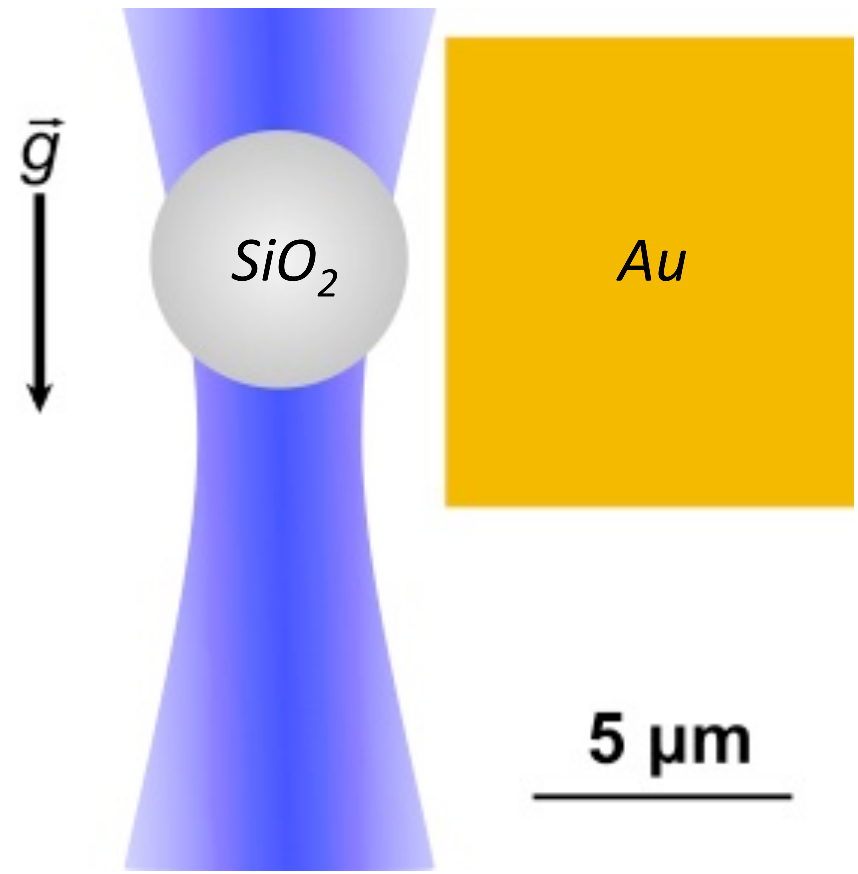
Optical levitation

- Previous measurements at short distance have used mechanical springs as force sensors (e.g. torsion pendulums, micromachined cantilevers)
- Suspending test mass with an “optical spring” offers several advantages:
  - Thermal and vibrational noise from mechanical support minimized
  - At high vacuum, test mass can be isolated from surroundings and cooled optically (without cryogenics)
  - Test mass position can be controlled and measured precisely with optics
  - Dielectric spheres with a wide range of sizes (~10 nm – 10 μm) can be used
  - Extremely low dissipation is possible: $Q \sim 10^{12}$ at 10^{-10} mbar

Geraci et al., PRL ***105****, 101101 (2010)*

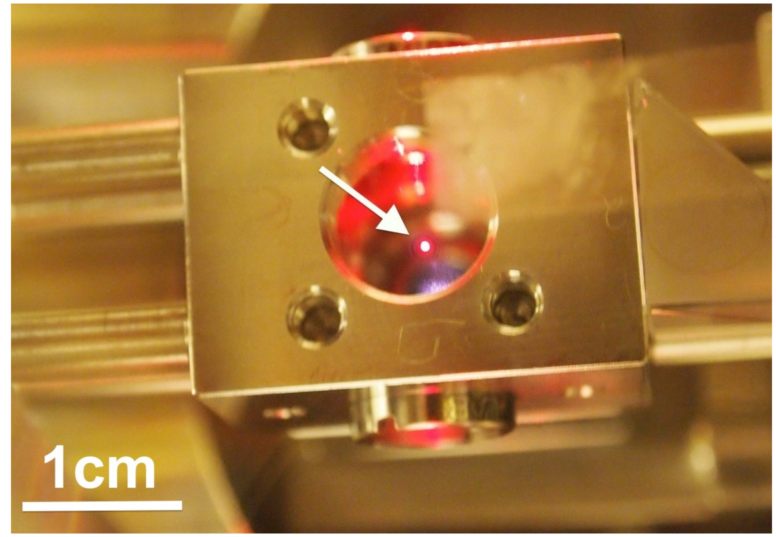
Schematic of optical levitation technique:



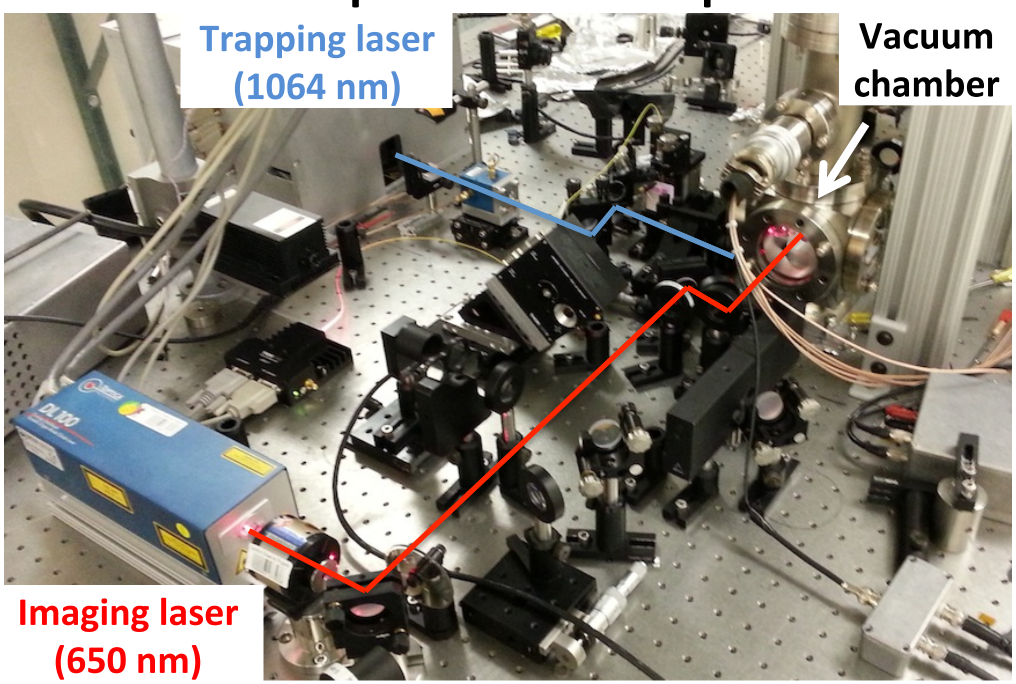
Experimental setup

- Developed setup capable of levitating SiO_2 microspheres with r = 0.5-5 μm
- Microspheres are levitated in vacuum chamber with λ = 1064 nm, ~few mW trapping laser
- Imaged by additional λ = 650 nm beams
- Have demonstrated trapping times of >100 hrs at ~10^{-7} mbar

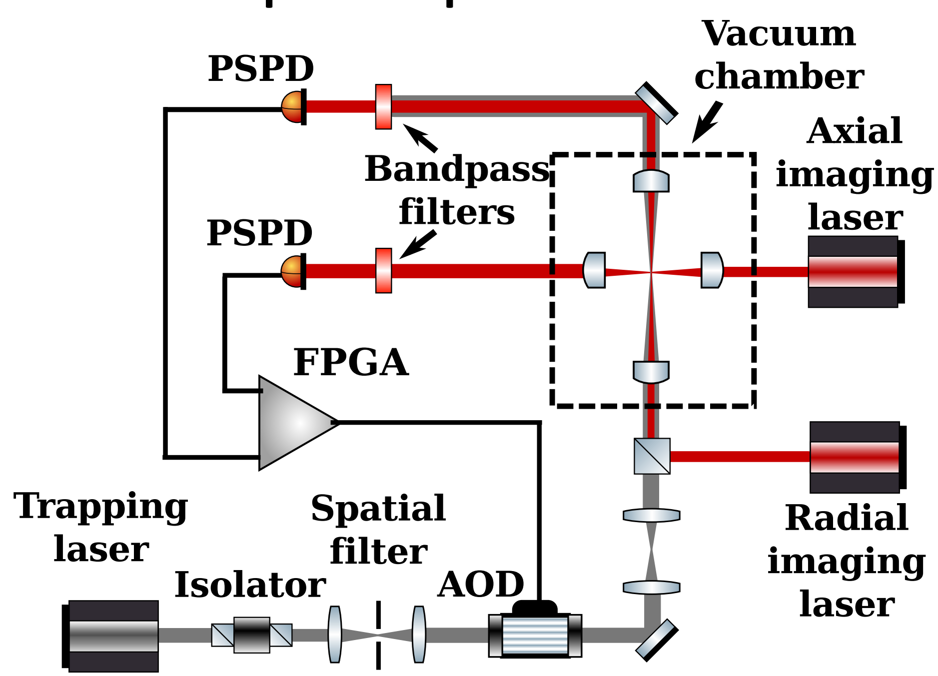
Photograph of trapped microsphere:



Experimental setup:



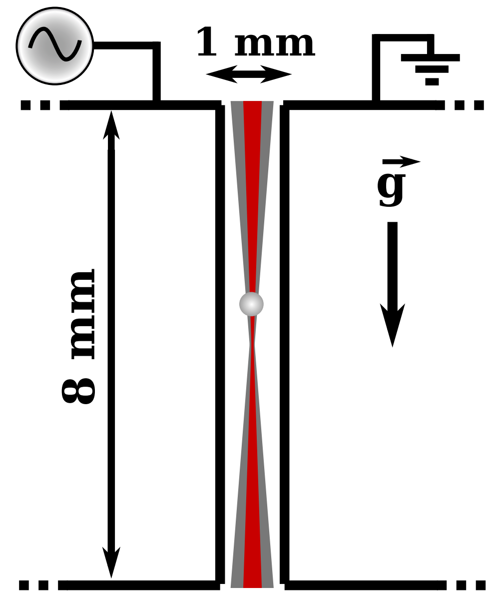
Simplified optical schematic:



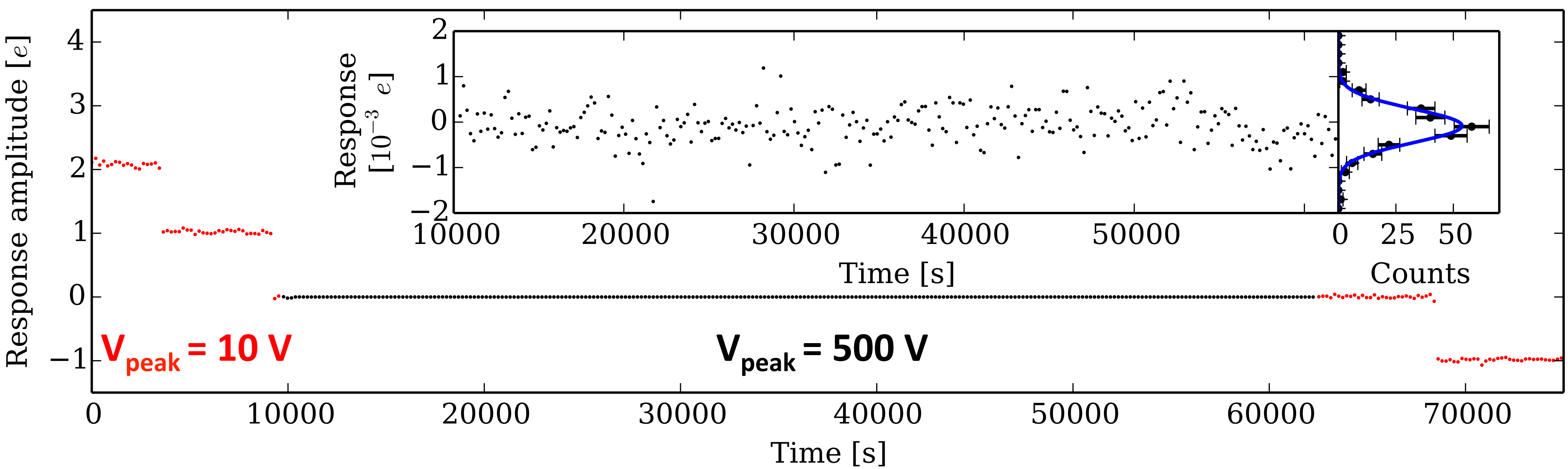
Microsphere neutralization

- Electromagnetic backgrounds can overwhelm signal from new short-range forces
- Have demonstrated controlled discharging with single e precision
- Once neutral, microspheres have not spontaneously charged in total integration time of more than 10^6 s
- Also measure force sensitivity for each microsphere *in situ*: $\boldsymbol{\sigma_F = 5 \times 10^{-17}}$ **N Hz$^{-1/2}$**

Electrode configuration:



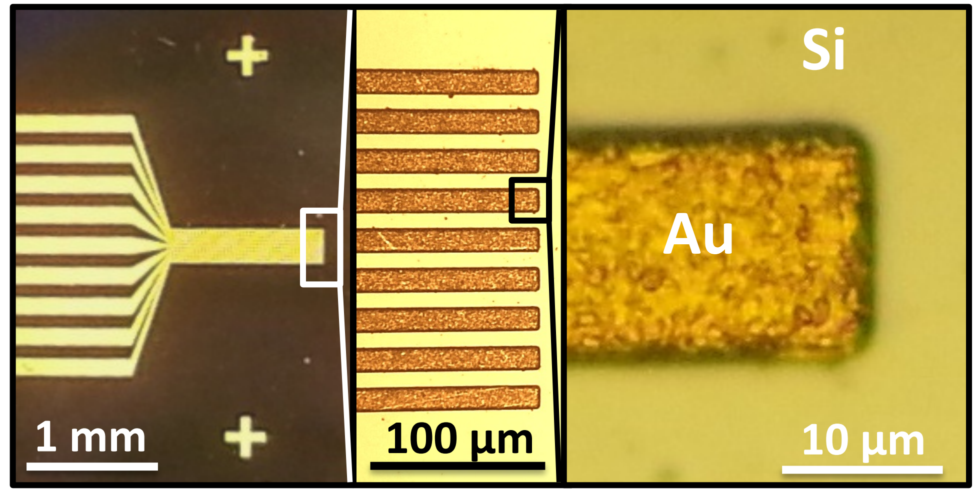
Example of discharging process:



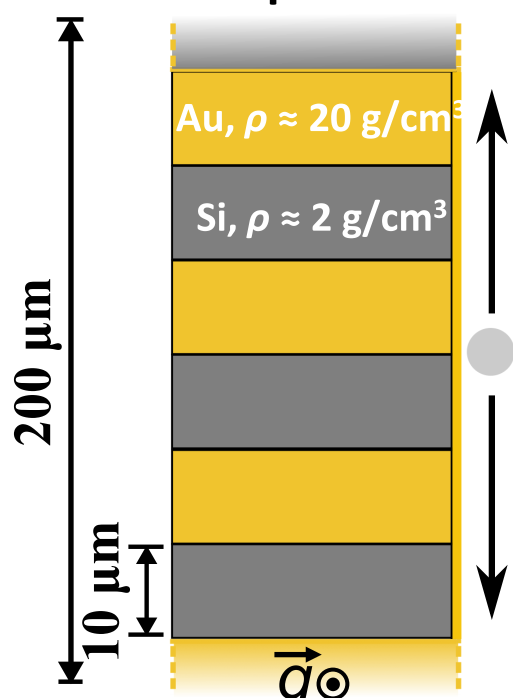
Attractor design

- Short-range force measurements require gravitational attractor that can be positioned near microsphere
- Attractor with spatially varying density allows reduction of many backgrounds
- Have begun fabrication of Au and Si test mass arrays
- Au shielding layer screens electromagnetic backgrounds that vary with composition

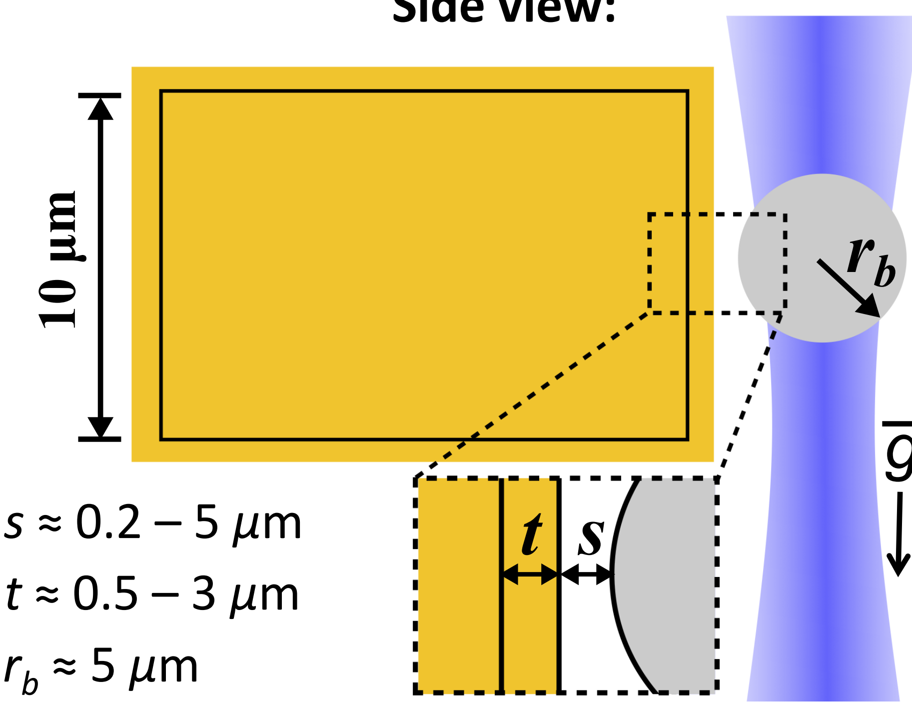
Images of preliminary fabrication tests:



Top view:



Side view:



$s \approx 0.2 - 5\ \mu m$

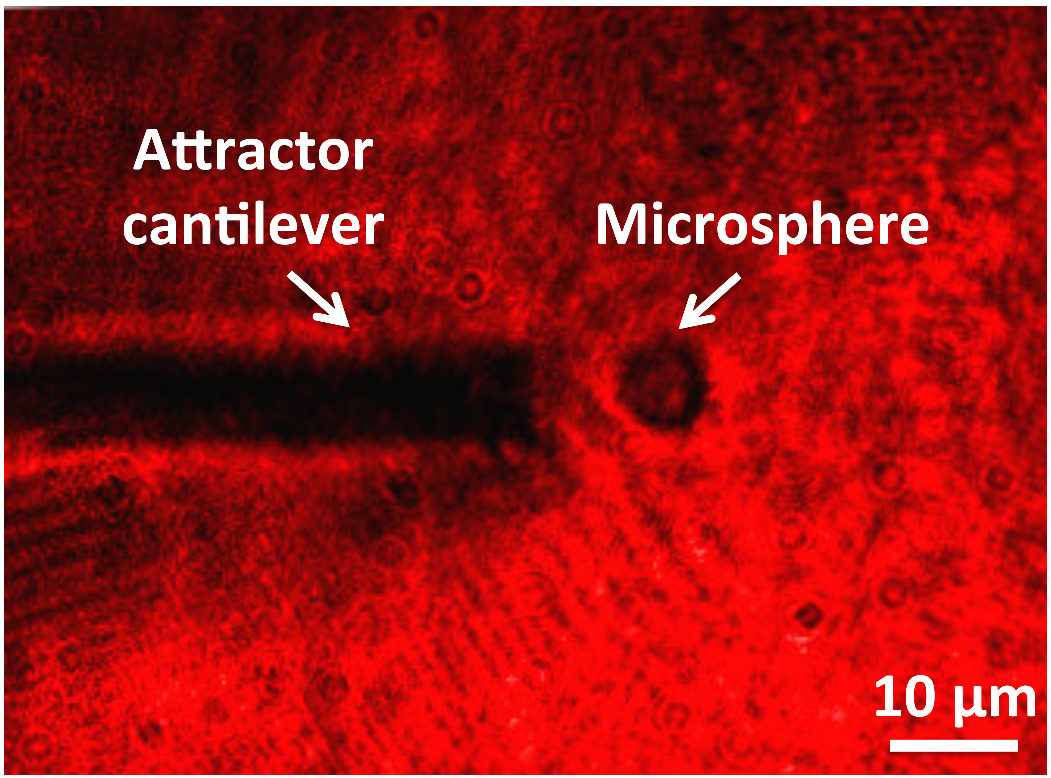
$t \approx 0.5 - 3\ \mu m$

$r_b \approx 5\ \mu m$

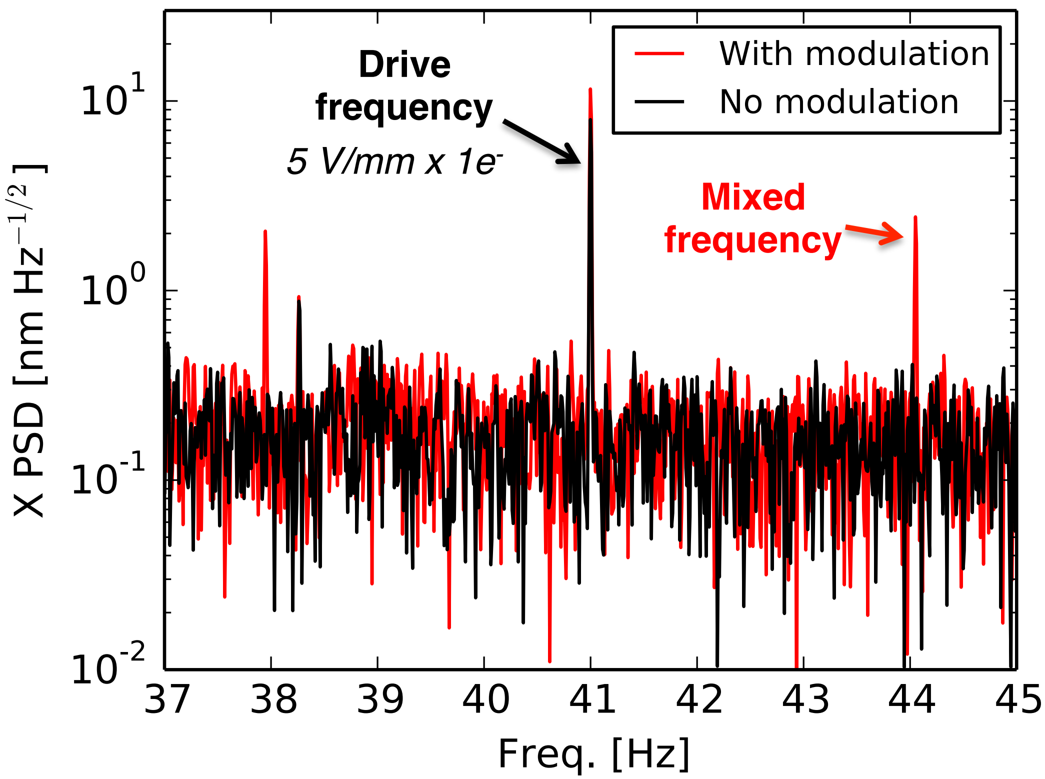
Microsphere positioning

- The optical trap can be precisely controlled using the acousto-optic deflector (AOD)
- Microsphere can be positioned with micron separations from the attractor and swept along the face at up to 200 Hz
- Can also “jitter” trap at frequencies above microsphere response to modulate spring constant and mix signal away from harmonics of motion

Side view of microsphere near attractor:



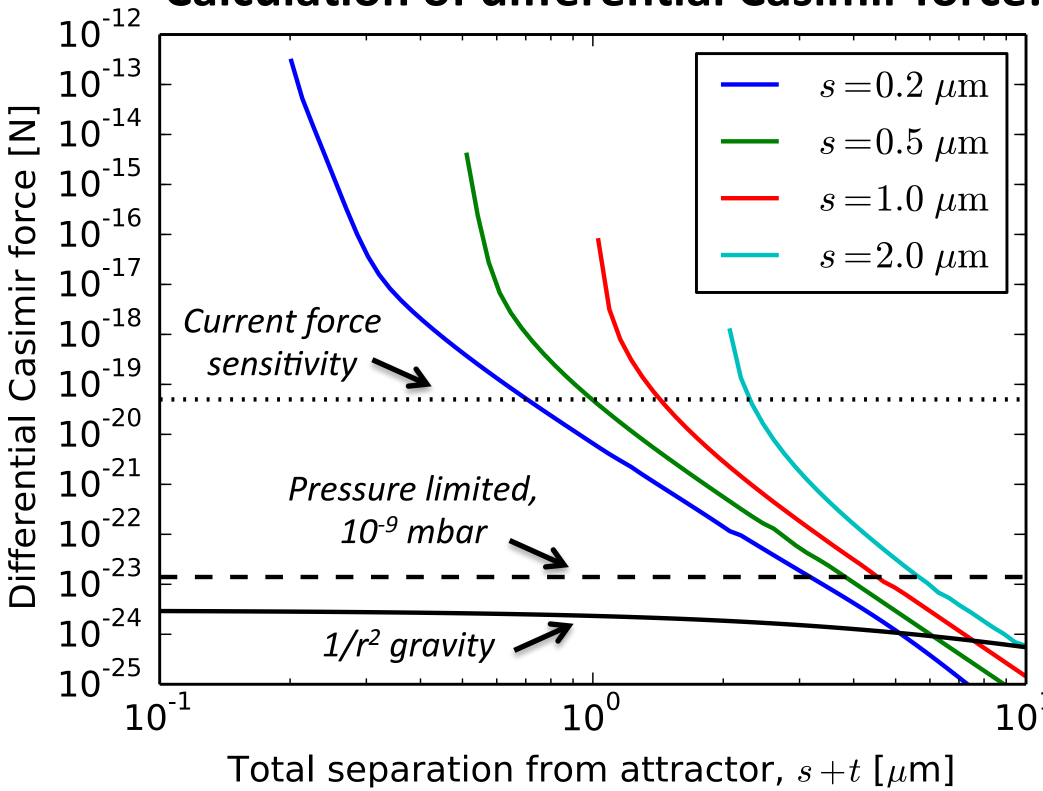
Example of trap modulation:



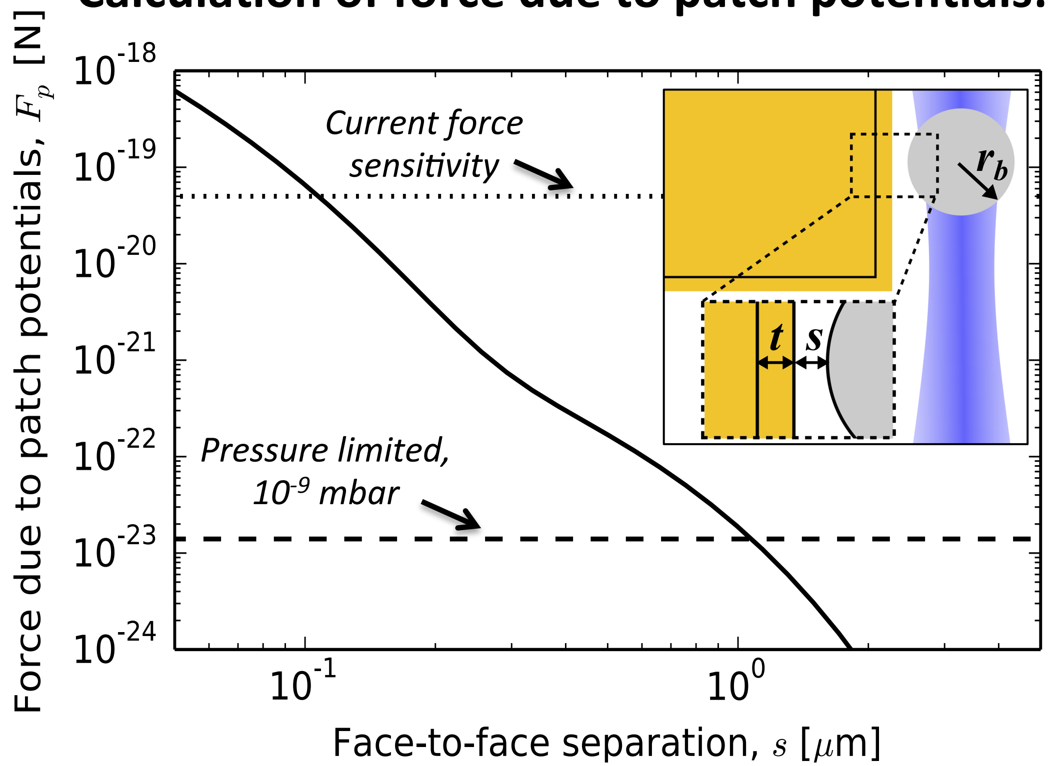
Additional backgrounds

- If unscreened, differential Casimir force between Au and Si can present dominant background
- Coating attractor with Au shield layer (0.5 to 3 μm thick) can sufficiently suppress this background
- Background force due to surface “patch potentials” should be subdominant for expected face-to-face separations

Calculation of differential Casimir force:



Calculation of force due to patch potentials:

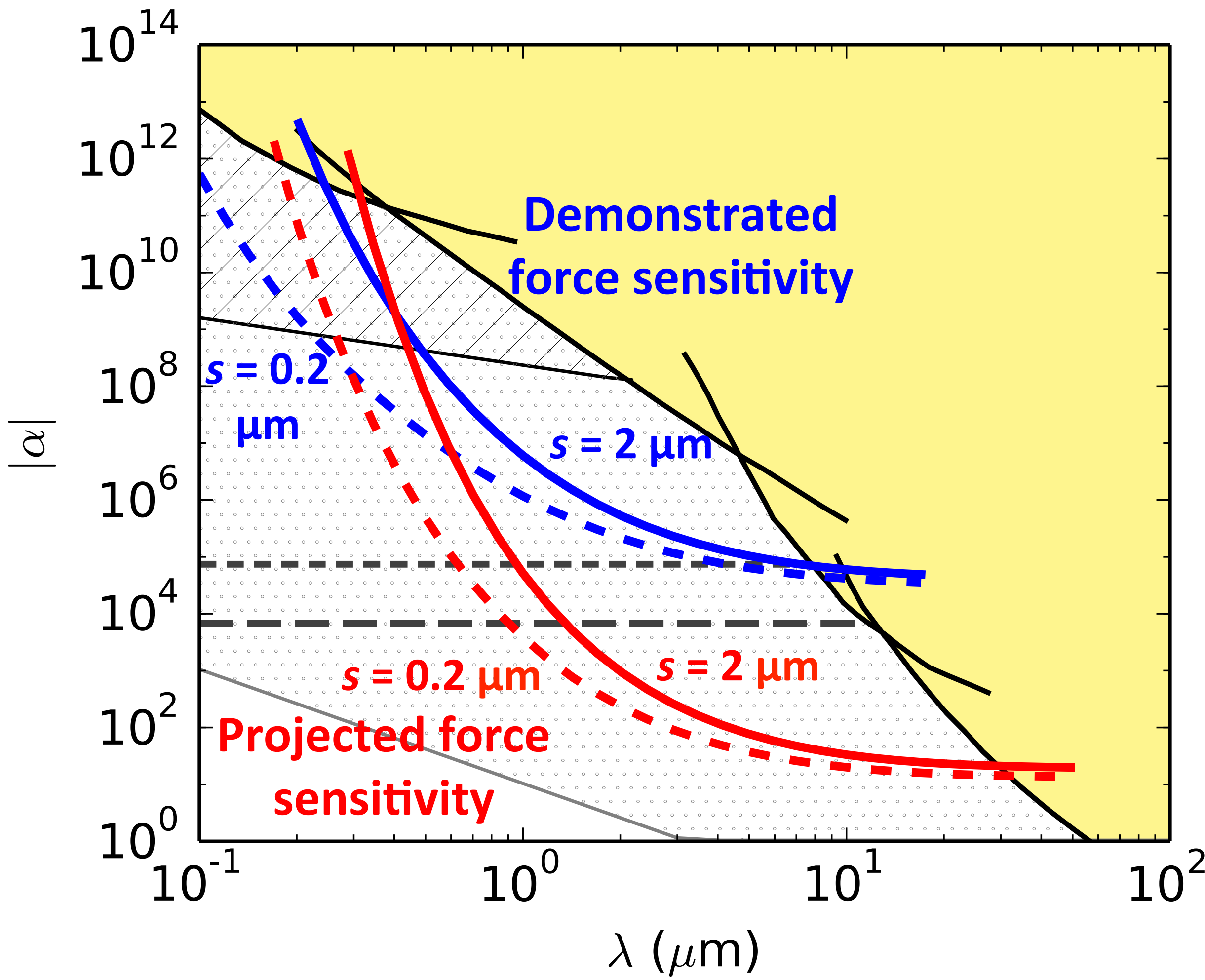


Expected sensitivity

- Have calculated expected sensitivity to Yukawa strength parameter, α, as a function of length scale, λ
- Assume face-to-face separation of $s = 0.2$ μm (dashed) or 2 μm (solid)

- Plot sensitivity for demonstrated $\sigma_F = 5\text{x}10^{-17}$ N $\text{Hz}^{-1/2}$ (blue) and for pressure limited σ_F at 10^{-9} mbar (red)
- Assume Au shielding layer of sufficient thickness to make Casimir background negligible
- Improvement in sensitivity by several orders of magnitude over existing limits at 0.1–40 μm is possible
- Hatched regions, lines show selection of theoretical models from PRD **68** 124021 (2003)

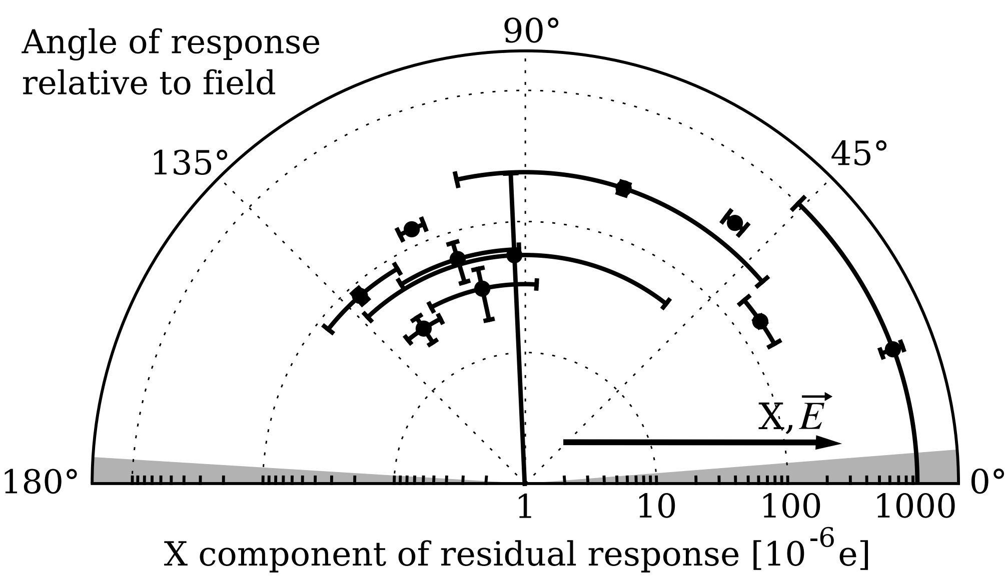
Projected sensitivity to non-Newtonian forces:



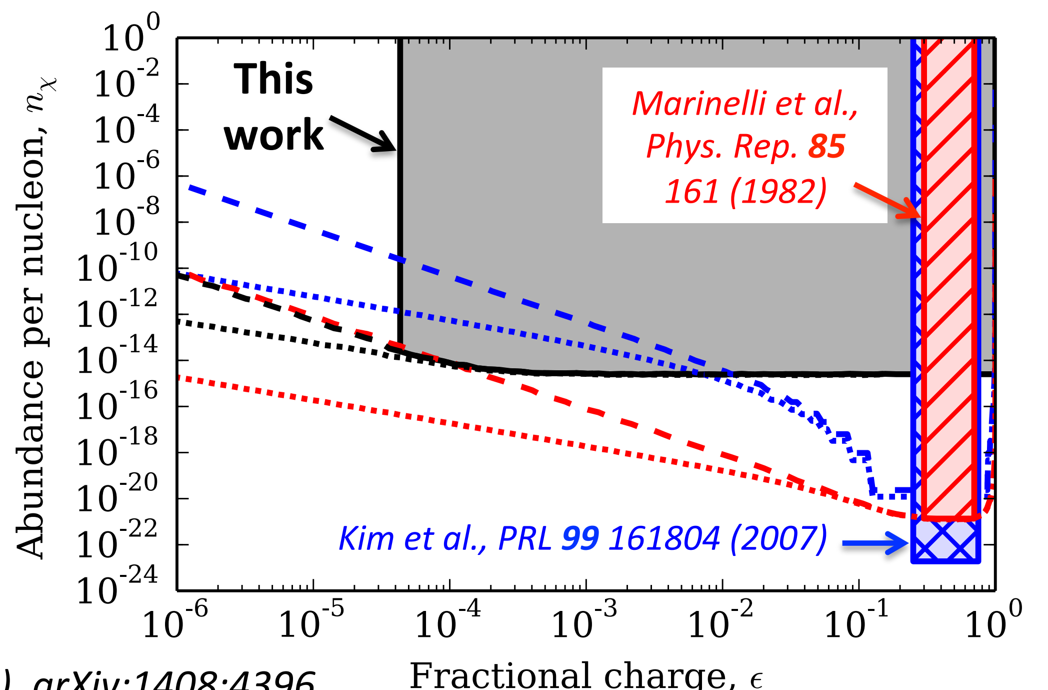
Heavy millicharged particles

- As a first application of this force sensing technique, we have performed a search for millicharged particles (|q| << 1e) bound in the microspheres
- Sensitive to single fractional charges as small as 5 x 10^{-5} e
- Current sensitivity (<1 aN) limited by residual response due to microsphere inhomogeneities that couple to E-field gradients

Measured residual response:



Limits on abundance of millicharged particles:



Moore et al., Phys. Rev. Lett. ***113*** *251801 (2014), arXiv:1408:4396*

Coulomb's law

- Dark photons or millicharged particles from a hidden sector could lead to deviations from Coulomb's law at short distance:

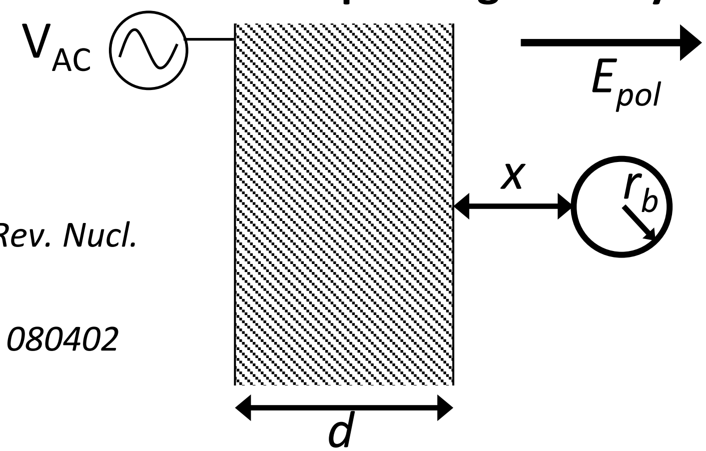
Dark photon: $$V(r) = \frac{e^2}{r}\left(1 + \chi^2 e^{-m_\Gamma r}\right)$$

Jaeckel and Ringwald, Ann. Rev. Nucl. Part. Sci., ***60****, 405 (2010)*

Light MCP: $$V(r) \approx \frac{\alpha}{r}\left[1 + \frac{\alpha\epsilon^2}{4\sqrt{\pi}}\frac{\exp(-2mr)}{(mr)^{\frac{3}{2}}}\right]$$

Jaeckel, Phys. Rev. Lett. ***103****, 080402 (2009)*

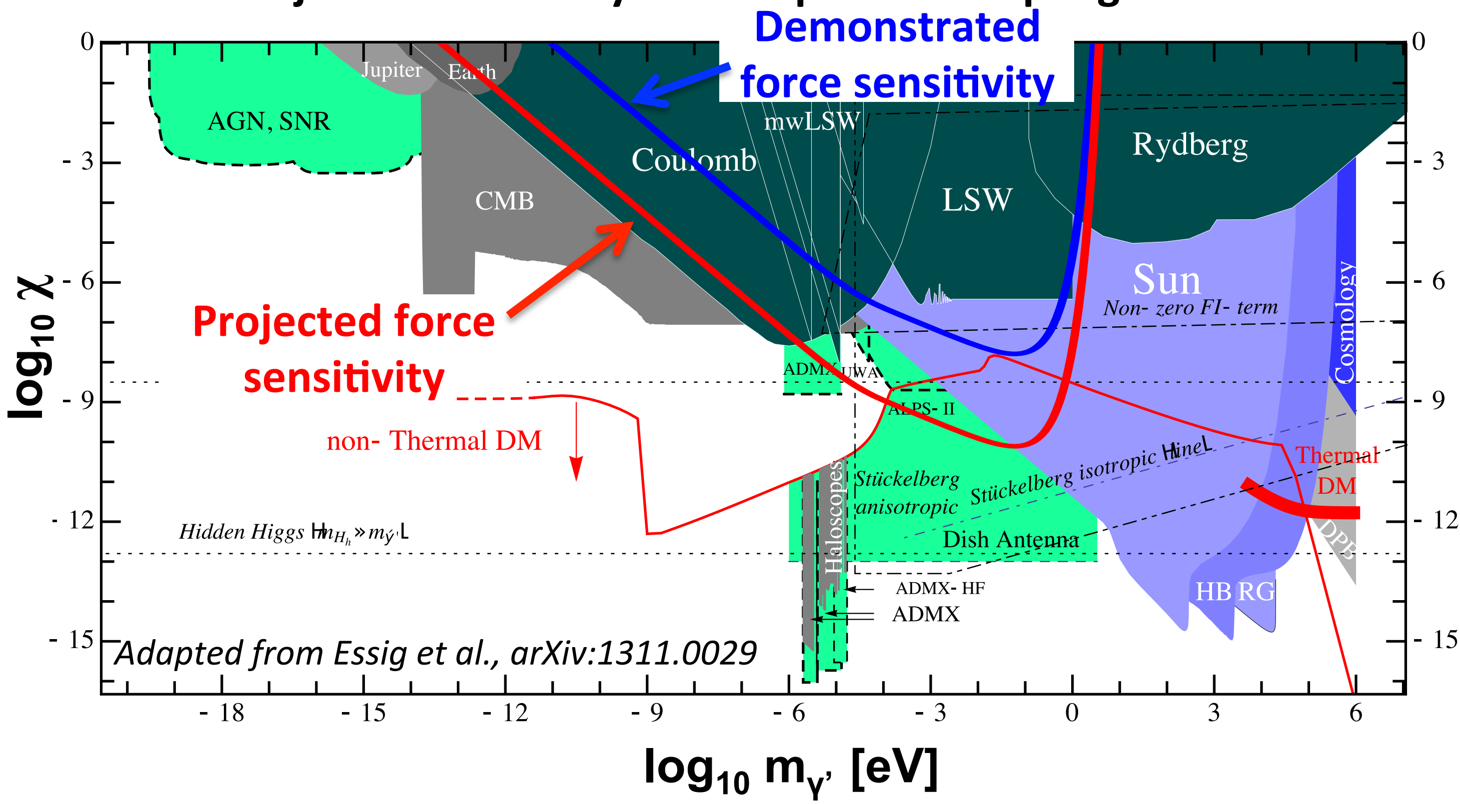
Schematic of simplified geometry:



- Significant increase in sensitivity possible for ~meV masses

- Calculation assumes:
  - $d \approx 1$ mm
  - $x \approx 1$ μm – 100 μm
  - $V_{AC} \approx$ ±10 kV, ±50 kV
  - $E_{pol} \approx 10$ kV/mm
  - $\sigma_F = 5\times10^{-17}$ N Hz$^{-1/2}$
  - σ_F = pressure limited at 10^{-9} mbar

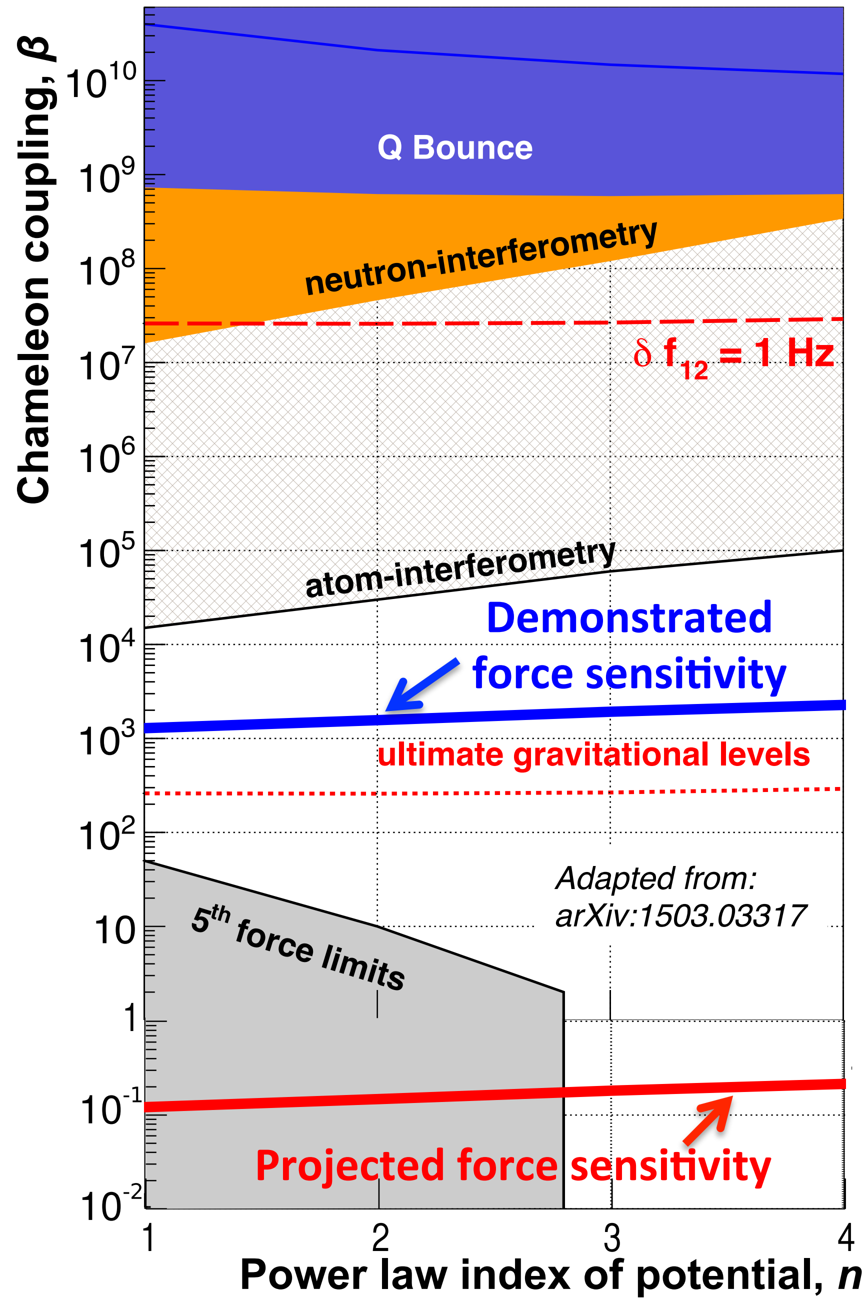
Projected sensitivity to dark photon coupling vs. mass:



Chameleons

- There has been recent theoretical interest in light scalars with screened interactions at short distances
- In the “chameleon” mechanism, the effective mass becomes large in high density regions
- Microspheres in our geometry are not substantially screened for $\beta < 10^8$
- Can search for new forces below dark energy length scale **Λ ~ 80 μm**
- Allows sensitivity to larger couplings, β, than torsion pendula
- Could substantially improve on current constraints from neutron and atom interferometry

Constraints on power law chameleons:



Summary

- Levitated microspheres can enable novel searches for a variety of models that can account for dark matter or dark energy
- Ability to control charge state and optical potential allows precise measurement and mitigation of electrostatic backgrounds
- Have demonstrated force sensitivity $<10^{-18}$ N, but substantial improvement is possible
- Can probe significant amounts of unexplored parameter space for new forces coupling to mass at length scales from 0.1 – 40 µm
- Also will enable sensitive searches for dark photons, millicharged particles, and chameleon dark energy models